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Complete List of Authors:	White, Tom; University of Oxford, Research Laboratory for Archaeology and the History of Art Bridgland, David; University of Durham, Department of Geography Westaway, Rob; University of Glasgow, School of Engineering Straw, Allan
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Evidence for late Middle Pleistocene glaciation of the British margin of the southern North Sea

Tom S. White*[1], David R. Bridgland[2], Rob Westaway[3,4] and Allan Straw[5]

[1] Research Laboratory for Archaeology and the History of Art, University of Oxford, Hayes House, 75 George Street, Oxford OX1 2BQ, UK
[2] Department of Geography, Durham University, South Road, Durham DH1 3LE, UK
[3] School of Engineering, University of Glasgow, James Watt (South) Building, Glasgow G12 8QQ, UK
[4] Newcastle Institute for Research on Sustainability, Newcastle University, Devonshire Building, Newcastle upon Tyne NE1 7RU, U.K.
[5] 31 Tilmore Gardens, Petersfield GU32 2JE, UK

Abstract

The timing and extent of late Middle Pleistocene glaciations in England and the southern North Sea are controversial topics. The recent Trent Valley Palaeolithic Project uncovered evidence for a post-Anglian, pre-Devensian glaciation that affected much of central and eastern England; the Wragby Till of Lincolnshire is associated with this glacial event, attributed here to MIS 8. Coeval glacigenic deposits in the Middle Trent suggest that both western and eastern lobes of MIS 8 ice reached the Derby area. These various deposits have been assigned previously to MIS 12, 10 or 6, although the last can be excluded for the Wragby Till, which is overlain by Trent terrace deposits assigned to MIS 7 (from biostratigraphy and amino-acid dating). The disposition of these glacigenic deposits within the landscape, particularly in relation to terrace deposits of the ancestral River Trent, and the absence of MIS 11 and 9 deposits within the footprint of the glaciation also provide compelling evidence. At its maximum extent in eastern England the MIS 8 ice reached the Peterborough area; identifying its extension (or otherwise) into areas such as NW Norfolk and the West Midlands requires further work.

*corresponding author: tom.white@rlaha.ox.ac.uk

Key words:

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Introduction

The evidence for the timing and extent of lowland glaciation in Britain between the Anglian (MIS 12) and Devensian (MIS 2) has been a matter of long-standing debate. This paper reviews the evidence for post-Anglian–pre-Devensian glaciation at the western margin of the southern North Sea basin, a critical area where pertinent evidence has long been recognized and where recent reappraisal has sharpened focus on the topic. This new work has stemmed from the 'Trent Valley Palaeolithic Project' (TVPP: see acknowledgments).

In 1973 the Geological Society of London (GSL) Quaternary correlation booklet (Mitchell *et al*., 1973) proposed a British terrestrial 'climato-stratigraphy' that included a glacial and corresponding glaciation later than the Anglian but before the Devensian. Termed the Wolstonian, with a type locality at Wolston, east of Coventry, this was a late substitute for the 'Gippingian glaciation' that had been identified in the Gipping Valley near Ipswich, Suffolk. The substitution arose because research that was in the process of publication showed the 'Gipping Till' to be inseparable from the Anglian Lowestoft Till (Bristow and Cox, 1973; see also the published discussion of that paper). Previously there had been widespread agreement, since the multiple glaciations paradigm had replaced monoglacialism (cf. Imbrie and Imbrie, 1979), that lowland Britain had experienced at least three Quaternary glaciations (e.g., Clayton, 1953, 1957; West and Donner, 1956; Straw, 1958, 1969, 1979a; Catt, 1979, 1981). Subsequently, however, it was purported that much of the glacigenic signature of the Wolstonian, including the Upper Wolston Clay at the type locality (later synonymized with the Oadby Till: Rice, 1968, 1981; see below), formed part of a single chalky till sheet of Anglian age that extended across the English Midlands and East Anglia (e.g., Perrin *et al*., 1979; Sumbler, 1983a, b; Rose, 1987). Nonetheless, some authors (e.g. Gibbard and Turner, 1988, 1990; Gibbard and Clark, 2011) have continued to apply the term 'Wolstonian' to the interval between the Hoxnian (MIS 11) and the Ipswichian (MIS 5e), effectively applying that name to any cold-climate deposits from MIS 10, 8 or 6: i.e., to a lengthy and climatically complex span of time, incorporating parts of three 100 ka Milankovitch cycles.

Notwithstanding the above, it has long been clear that in restricted areas of Midland England there is evidence that cannot be explained other than in terms of an additional late Middle Pleistocene glaciation. Five areas, in particular, have provided such evidence:

1. NW Birmingham, where unequivocal evidence for post-Anglian–pre-Devensian glaciation occurs at Quinton and Nechells (Duigan, 1956; Kelly, 1964; Horton, 1974; Maddy, 1999; Thomas, 2001)
2. Lincolnshire, where Straw (1963, 1983, 2000, 2005, 2011) has long promoted glaciation during multiple stages.
3. the East Midlands, particularly the sedimentary archives preserved in the Trent and Witham valleys, newly reinterpreted as a result of the TVPP (White *et al*., 2010; Bridgland *et al*., 2014; Westaway et al., 2015)
4. the Fen Basin, where evidence for post-Anglian–pre-Devensian glaciation has been described from the valleys of the Nar (Gibbard *et al*., 1991, 1992, 2009; Lewis and Rose, 1991) and the Welland/Nene (Langford, 2004; Langford et al., 2014)
5. northern East Anglia, where the evidence for post-Anglian–pre-Devensian glaciation has been much debated (Straw, 1965, 1973, 1979a, b; Hamblin *et*

al., 2000, 2005; Westaway, 2010; Lee *et al*., 2011, 2012; Westaway *et al*., 2015).

Although pre-Devensian glacial deposits crop out across much of central and southern England (north of the Thames), it has long been evident that distinguishing between the products of different glaciations and attributing them to different pre-MIS 2 climate cycles is difficult (e.g. Shotton, 1983; Clark *et al*., 2004; Pawley et al., 2008; Boston et al., 2010). Indeed, in the absence of reliable geochronological techniques that can be applied directly to tills, the occurrence of sediments from multiple glaciations can only be established unequivocally if there are interbedded interglacial deposits or other evidence for interglacial conditions, such as palaeosols, separating glacial units.

River terrace sequences as a means for unravelling multi-glacial histories

Fluvial sequences, and in particular river terraces, represent valuable archives of landscape evolution (Bridgland and Westaway, 2014). They are also repositories for palaeoenvironmental evidence of various types, from sedimentological signatures of depositional regime to palaeontological indications of contemporaneous climates and environments (e.g., Bridgland, 2000, 2010; Bridgland and Maddy, 2002; Antoine *et al*., 2007; Schreve *et al*., 2007). Such archives also provide regional stratigraphical frameworks for long-timescale Quaternary terrestrial sequences, within which isolated records from other environments, such as lakes, can be positioned (cf. Bridgland *et al*., 2004; 2007; Bridgland and Westaway, 2014). Their value for unravelling multiple glacial sequences was recognized in the Alps, where they formed the basis for the original transition from monoglacialism (Penck and Bruckner, 1909; cf. Šibrava, 1986). For optimal value, the building of a stratigraphical framework from river terraces requires correlation with the marine oxygen isotope record, achievable using various methods, the suitability of which can vary from system to system; absolute dating techniques, such as optically stimulated luminescence (OSL), can sometimes be applied and, if preserved, fossil assemblages recovered from interglacial sediments can provide biostratigraphical dating control (e.g., Matoshko *et al*., 2004; Briant *et al*., 2006; Antoine *et al*., 2007; Schreve *et al*., 2007).

The value of this approach has been heightened in recent decades by the realisation that the progressive valley deepening that is recorded in river terrace sequences can be interpreted as a responsive to regional uplift during the Quaternary (Maddy, 1997; Bridgland, 2000, 2010). The latter is a widespread phenomenon that is characteristic of post-Precambrian crustal provinces and can be linked to accelerated erosional isostasy in response to enhanced surface processes, driven by the greater severity of Pleistocene climatic regimes (Westaway, 2002; Bridgland and Westaway 2008a, b, 2014). Such records of fluvial incision in response to regional uplift can be modelled numerically (e.g., Westaway *et al*., 2002, 2006); as part of the TVPP the wider Trent sequence has been modelled according to this rationale, using karstic evidence from the Dove and Derwent tributaries as well as the river terrace archives (Bridgland et al., 2014; Westaway *et al*., 2015). Thereby has been compiled the stratigraphical framework within which the evidence for late Middle Pleistocene glacial disruption of the Trent can be interpreted.

As a result of the TVPP, the valleys of the Lower Trent and Witham in Lincolnshire have been shown to have been glaciated during the late Middle Pleistocene; the stratigraphical disposition of the Wragby Till (cf. Straw, 1966, 1969, 1983) in relation both to the Trent terrace sequence and to the incision history of the Lower Witham valley, which was formed and occupied until the latest Devensian by the Trent (Bridgland et al., 2014), strongly implies a post-Anglian age for the Wragby glaciation (White *et al*., 2010; Bridgland *et al*., 2014). Most authors have interpreted evidence for post-Anglian–pre-Devensian glaciation in Britain as representative of MIS 6 (186–128 ka), which is widely acknowledged to correlate with the most extensive glaciation of the near continent: the Drenthe ice advance of the Netherlands (e.g., Busschers *et al*., 2008; Laban and van der Meer, 2011). In the updated GSL Quaternary correlation booklet (Bowen, 1999) the post-Hoxnian Ridgeacre Till at Quinton was assigned to that stage (Maddy, 1999), as was the Welton-le-Wold glaciation of Lincolnshire (Lewis, 1999) and the glaciation responsible for an outwash delta in north Norfolk, at Tottenhill, near King's Lynn (Gibbard *et al*., 1991, 1992; Lewis and Rose, 1991). The glacial deposits of the Cromer Ridge, North Norfolk, have also been suggested to date from MIS 6 (Hamblin *et al*., 2000, 2005; Lee *et al*., 2011, 2012; cf. Lee *et al*., 2013). Glaciation during MIS 10 (362–339 ka) has been suggested for parts of the pre-Devensian till cover of Midland England, based initially on evidence from the Thame valley (Sumbler, 1995, 2001) but extended to include the Oadby Till (Hamblin *et al*., 2005; Carney, 2007; Rose, 2009; Lee *et al*., 2011, 2012), which has otherwise been regarded as an eastern facies of the Anglian till sheet (cf. Lewis, 1999; Maddy, 1999).

However, evidence from a large part of the East Midlands studied during the TVPP points to MIS 8 (245–303 ka) as the age of some of the glacigenic deposits in that area, including the Wragby Till (White *et al*., 2010; Bridgland *et al*., 2014). It should be noted that Straw (2000, 2005) has previously assigned the Wragby glaciation to MIS 8 and has long regarded it and correlative tills in adjacent areas (e.g., the Calcethorpe Till of the Lincolnshire Wolds) as the product of a 'Saalian' ice advance across eastern Britain (e.g., Straw, 1958, 1979a, b, 1983). Indeed, he has reconstructed ice sheets that would now be attributed to this same glaciation originating from the North Sea and the Vale of York and penetrating the middle Trent region, the present area of the Vale of Belvoir and the Fen Basin, as well as beyond. The geomorphological arguments employed by Straw have often emphasized ice behaviour during advance and recession phases, whereas in the more sediments-based TVPP synthesis the deglacial record invariably dominates, since this is what provides the main sedimentary archive of any particular glacial event.

Evidence from the TVPP 1: the Wragby Till of Lincolnshire

It is well known that glaciation can emplace deposits well below the general pre-glacial base level through glacial overdeepening and subglacial water flowing under hydrostatic pressure, with the deepest sub-base-level deposits generally being found in 'tunnel valleys' (e.g., Woodland, 1970; Ehlers *et al*., 1984; Ó'Cofaigh, 1996; Van Dijke and Veldkamp, 1996; Kristensen *et al*., 2008). Otherwise, however, the typical product of lowland glaciation is a widespread undulating plain covered by till, glacial outwash and glacio-lacustrine deposits, as seen in Cheshire, where it is the result of the Late Devensian (MIS 2) glaciation, and in East Anglia, primarily the result of the Anglian (MIS 12) glaciation. In the latter region post-Anglian rivers have incised valleys, complete with terrace systems, into the glaciated plain, which is essentially a plateau, and often into underlying bedrock, although in some cases pre-glacial drainage systems and tunnel valleys occur at positions in the landscape comparable with the modern valley bottoms (e.g., the Bytham River and associated Lark–Waveney Tunnel Valley: Bridgland and Lewis, 1991). In contrast the Wragby Till of central Lincolnshire is disposed at a low level in the area of the Witham valley, its base falling below the height of the floor of the tidal reach (Fig. 1) and well below the reconstructed level of the landscape that would have existed prior to the Anglian glaciation (cf. Bridgland *et al*., 2014; Westaway et al., 2015). This geometry of the Wragby Till does not take the form of a tunnel valley infill, although it has been interpreted as infilling the wider confines of a fluvial palaeovalley, one formed in the late Middle Pleistocene following the breach of the Chalk escarpment in the area of the modern Fen Basin during the Anglian glaciation (Bridgland *et al*., 2014; Westaway et al., 2015; cf. Straw, 1958, 1979a, figure 4.2). Prior to this breach the Bytham River traversed this region and extended into Norfolk and Suffolk (Fig. 2A). Although the breach of the Chalk, and the destruction of the Bytham River, was effected by the Anglian glaciation, the palaeovalley in which the Wragby Till was emplaced is attributed to an early (proto-) Trent (proto-Trent/Langworth: Fig. 2B) drainage system, which has left little other trace in the landscape.

Although disposed at a lower level, the Wragby Till of central Lincolnshire exhibits characteristic 'glaciated plain' features. Around Wragby the till surface is plain-like and, to the north, the Ancholme and its tributaries have dissected the till sheet into discrete spur-cappings and removed it altogether below Brigg. Straw (1958) has described the morphology of the sub-till surface, revealing it to be a broad symmetrical depression declining south beneath the Witham and fenland deposits, its axis followed by the Ancholme and the Langworth tributary of the Witham and its westward slope coinciding closely with the dipslope of the erosion-resistant Jurassic oolitic limestone. Eastward the edge of the vale rises with similar gradient across Kimmeridge Clay to the foot of the Cretaceous escarpment. Notwithstanding the geological control, the symmetry and smoothness of the depression are features that are perhaps suggestive to ice erosion, although this is likely to have been modification of a pre-existing strike vale, very much like the modern one. Such erosion was not confined to central Lincolnshire. Straw has referred on many occasions to the occurrence and significance of glacial erosion over Lincolnshire (e.g. Straw, 1958, 1969, 1979a, b, 1983) and to the incremental development of the Fen Basin, where latterly the Wragby ice merged with North Sea ice that had moved south over the Wolds and perhaps finally breached the Chalk scarp to produce the Wash gap (Straw 1979b).

The Wragby glaciation is attributed to MIS 8, in confirmation of the views of Straw (2000, 2005), for the following reasons:

1. ***The stratigraphical disposition of the till in relation to the Lower Witham terraces***

   The Eagle Moor–Martin Terrace is attributed to MIS 8 and its gravel carries outwash from the glaciation (indicated by relatively abundant flint and other glacially-derived material, such as *Rhaxella* chert) as well as overlying the till downstream of Lincoln and glacio-lacustrine deposits (Skellingthorpe Clay) upstream of Lincoln (White *et al*., 2010; Bridgland *et al*., 2014).

2. ***Biostratigraphy***

   The next terrace in the sequence, the Balderton–Southrey, overlies and is inset into the Wragby Till and includes MIS 7 deposits at a number of localities both upstream and downstream of Lincoln (Brandon and Sumbler, 1988, 1991; White *et al*., 2010; Bridgland *et al*., 2014; Fig. 3).

3. ***Glacio-isostasy***

   The Eagle Moor–Martin Terrace is bi-facetted, both upstream and downstream of Lincoln, the upper and lower facets being regarded as equivalents, respectively, of the Sandiacre and Etwall terraces of the Middle Trent, both within the upper part of the multi-facetted 'Hilton Terrace Complex' of that region (Bridgland *et al*., 2014, 2015; Fig. 4; Table 1). The 'Upper Hilton Terrace' has long been associated with glaciation (Posnansky, 1960; Straw, 1963; see below), and the facets are attributed to the effects of glacio-isostatic rebound as the 'Wragby' ice sheet diminished and ultimately disappeared (Bridgland *et al*., 2014).

4. ***Absence of post MIS 12/pre MIS 8 deposits***

   Albeit a negative and thus inherently weak line of evidence, the complete absence of the deposits of these two Milankovitch cycles (cf. Howard *et al*., 2007; White *et al*., 2010) is compelling in comparison with areas to the south and south-east, where interglacial deposits representing the Hoxnian (MIS 11) and MIS 9 (the 'Purfleet interglacial') are an important part of the Quaternary record (Fig. 5).

Evidence from the TVPP 2: the 'Hilton Terrace' glaciation of the Middle Trent

The Middle Trent, in the vicinity of Derby and Nottingham, is the reach within which the 'classic' Trent terrace sequence was established by Clayton (1953). This sequence was tripartite, consisting of an upper 'Hilton Terrace', recognized to be multiple (Clayton, 1953; Posnansky, 1960; cf. Pocock, 1929), a middle 'Beeston Terrace' and a lower 'Floodplain Terrace'. The nomenclature has been modified and extended by subsequent authors (see Table 1) but a key element remains: the sequence begins with the uppermost Hilton Terrace, associated, as already noted (e.g., on the basis of diamicton inclusions within the gravels), with glaciation. By analogy with the stratigraphical relations in Lincolnshire and the correlation of terraces between the two areas, already summarized, this glaciation would again appear likely to date from MIS 8. From the above list of numbered points, 3 and 4 apply once again. Regarding point 2, there are no MIS 7 deposits upstream of Nottingham, but Last Interglacial (Ipswichian: MIS 5e) deposits occur in the tributary Derwent valley, in the Allenton (= Beeston) terrace deposits of that river, which is younger than the Egginton Common–Balderton terrace, within which (downstream of Nottingham) MIS 7 deposits occur (Table 1). Thus the biostratigraphy is consistent between the two areas and with the attribution of the glaciation to MIS 8. Added to these arguments are a new set of points in favour of this interpretation, as follows.

Disposition of sediments and the inter-relations between glacial and fluvial deposits.

The glacial deposits of the Middle Trent occur as tills flanking the valley, the latter having been incised through them (see above), and within deep subsurface channels that have been interpreted as tunnel valleys. In particular, to the SW of Derby is a pair of deeply incised subsurface valleys: the Elvaston Channel and the Swarkestone Channel, their bases ~25 m below the level of the modern Trent floodplain in this reach. They contain glacio-lacustrine sediments and tills of both western and eastern facies, termed Thrussington Till and Oadby Till, these names carrying the implication (cf. Maddy, 1999) that they are Anglian. The depth of these features below the reconstructed Anglian landscape (cf. Westaway, 2007) would, given their width, be excessive, even for tunnel valleys. Furthermore, the Elvaston Channel deposits are closely associated with the 'Hilton Terrace Complex' in the region of Chellaston, where ice-proximal outwash gravels would appear to represent an even higher facet of that terrace than the Sandiacre Terrace (cf. Table 1). Thus they can be attributed to the same post-Anglian–pre-Devensian glaciation that emplaced the Wragby till. It would appear, from the occurrence of both Thrussington and Oadby 'facies', that both western and eastern lobes of ice penetrated the Middle Trent during this glaciation. This serves to confirm the reconstruction of this glaciation by Straw (e.g., 1983), although it raises a question over the supposed fluvial occupation of the Trent Trench since Anglian deglaciation (cf. Bridgland *et al*., 2014; Fig. 4). Indeed, Straw (1963) envisaged the trench as formed by meltwater drainage along the NW margin of a block of stagnant ice, occupying the Vale of Belvoir, at the end of what would here be termed the Wragby glaciation. The Vale of Belvoir was envisaged from TVPP data to have been excavated predominantly during the last two climatic cycles by the Smite–Devon, a south-bank Trent tributary system (Bridgland *et al*., 2014). Straw's (1963) suggestion that these streams were superimposed from (Wragby) subglacial drainage provides a plausible linkage between these interpretations.

Importance of this glaciation in the evolution of the Middle Trent.

Although the Derwent already existed in pre-Anglian times as a tributary of the Bytham (Brandon, 1995; Carney *et al*., 2001; Fig. 2A), there appears to have been no W–E aligned Trent valley prior to the MIS 8 glaciation. This is evidenced by low-level palaeo-Derwent gravel detected in a borehole at Hathern, in the Soar valley (Bridgland *et al*., 2014; cf. Maddy, 1999), which shows that the Derwent continued to flow south of the modern Trent valley after the Anglian, and after the destruction of the Bytham. This gravel is attributed to a Derwent–Soar 'palaeo-Trent' system (Fig. 2B). It is thought that the cutting of the Elvaston and Swarkestone channel systems during the MIS 8 glaciation was a prelude to the establishment of the modern W–E alignment of the Trent across the N–S aligned Derwent course (Fig. 2C/D). Indeed, the evident absence of a W–E aligned Trent prior to MIS 8 is important further evidence in attributing the Elvaston and Swarkestone channels to the Wragby glaciation. Till overlying the Hathern Gravel, of Thrussington facies, is attributed to the western lobe of MIS 8 ice (Fig. 6).

Association of late Middle Pleistocene glaciation with the Lower Palaeolithic record of the Trent.

The occurrence of Lower Palaeolithic artefacts in the gravels of the Middle Trent (Posnansky, 1963) provided an important rationale for the funding of the TVPP. A key finding of the project was that the archaeology occurs predominantly in the gravel of the Etwall (= Upper Hilton) Terrace, which incorporates outwash from the Wragby glaciation, the Palaeolithic archive taking the form of a mixed, highly abraded and frost-shattered assemblage that was swept from the pre-MIS 8 landscape and incorporated in these sediments (Bridgland *et al*., 2014). These observations accord with those of Wymer and Straw (1977), who noted the relatively meagre presence of Palaeolithic material to the north of a line from the Bristol Channel to the Wash and opined that the passage of ice over a landscape is likely to destroy most, if not all, of the soils and superficial materials.

Regional comparison: the Fen Basin

Prior to the latest Pleistocene, during deposition of the Holme Pierrepont Sand and Gravel (= Floodplain Terrace), the Trent was the principal river draining into the North Sea via the Fen Basin; its diversion to the Humber coincided with Devensian deglaciation (Bridgland *et al*., 2014, 2015; Fig. 2D–E). Downstream of the Tattershall area, where Trent terrace deposits and those of its left-bank tributary, the Bain, overlie Wragby Till, there is no further record of the Pleistocene, as the surface outcrop is dominated by Holocene fenland sediments. Other Fen Basin rivers also have important Middle–Late Pleistocene records, however, some of them pertaining to the history of glaciation in the region (cf. Boreham *et al*., 2010).

For example, in the Welland valley cross-bedded sand and gravel with a highly varied composition, including much non-durable material, has been interpreted as glacial in origin (Booth, 1981; Langford, 2004). Langford (2004) recorded exposures at Uffington, Lincolnshire that, on sedimentological grounds and in the absence of any geomorphological evidence, he regarded as ice-marginal glacial outwash. This interpretation was subsequently confirmed by work as part of the TVPP, when the gravel was shown to contain characteristic glacial clast types, including *Rhaxella* chert (Bridgland *et al*., 2014). Langford also mapped (following Kellaway and Taylor, 1953) a meltwater channel between the Welland and Nene valleys and glaciolacustrine deposits to the west of Peterborough, associating all of this evidence with a post-Anglian–pre-Devensian glaciation. Langford considered the minimum age of this glaciation to be MIS 8, from its relation to MIS 7 interglacial deposits within Nene Terrace 2 (Langford *et al*., 2004; Langford & Briant, 2004). Initially it was suggested (Langford and Briant, 2004) that the Tottenhill glacial outwash delta in the Nar Valley, southern Fenland (see above), represented this same glaciation, but subsequently, Langford (2012) has envisaged Fenland glaciation during both MIS 8 and MIS 6, favouring the younger age for Tottenhill (cf. Gibbard *et al*., 1991, 1992, 2009; see above).

The age of the Tottenhill sequence, including the underlying Nar Valley Beds as well as the deltaic glacial outwash gravel, has been much debated. The outwash deposits were assigned to MIS 6 by Lewis (1999), an interpretation also favoured by Gibbard and Clark (2011) and Gibbard *et al*. (2012a, b). The debate has been complicated by the inclusion of sediments at sites such as Warren Hill, High Lodge, Lakenheath, Feltwell and Shouldham Thorpe (Fig. 5), all of which have long-standing association with the pre-Anglian Bytham River (Bridgland and Lewis, 1991; Lee et al., 2004; Westaway, 2009), within a more widespread glacial outwash system, dated 'Late Wolstonian' or MIS 6 (Gibbard and Clark, 2011; Gibbard *et al*., 2012a, b, 2013; West *et al*., 2014). This suggestion of extensive late Middle Pleistocene glacial outwash has been refuted by Bridgland *et al*. (2014; 2015) on the grounds of the clear clast-lithological distinction between true glacial deposits and the gravels of the Bytham system, which have a more restricted composition and lack glacial indicators. The Bytham River deposits at Warren Hill, suggested by Gibbard and others to be part of the glacial outwash system, are an important source of Palaeolithic artefacts (Wymer, 1985, 1999; Hardaker, 2012), including tool forms now regarded as characteristic of pre-Anglian assemblages (Bridgland and White, 2014), thus reinforcing the view that they do not represent the late Middle Pleistocene glacial event.

White *et al*. (2010) and Bridgland *et al*. (2014) have suggested that the Tottenhill outwash delta represents the same glaciation as the Wragby Till of the Lower Trent/Witham valley. OSL dating of the Tottenhill Sand and Gravel, however, has yielded age estimates that place it within MIS 6 (Gibbard and Clark, 2011; Gibbard *et al*., 2012a, b; S. Pawley, pers. comm.). If this unpublished dating is correct, the implication is that a North Sea ice lobe reached the Fen Basin during MIS 6, probably limited to the area presently offshore and certainly with a smaller footprint than the Wragby Till ice in south Lincolnshire and, it would seem, the MIS 2 ice in north Norfolk, since it did not destroy the raised beach at Morston (Hoare *et al*., 2009; see below).

Regional comparison: northern East Anglia

Following the discrediting of the Gipping glaciation (see above), few authors considered the possibility of a post-Anglian–pre-Devensian glaciation in East Anglia prior to the emergence of the 'New Glacial Stratigraphy' (NGS) as proposed by Hamblin *et al*., 2000, 2005). Nonetheless Straw (1958, 1965, 1973, 1979b, 1983, 1991, 2000, 2005, 2011) has persistently correlated the stratigraphically youngest pre-Devensian glacial deposits in NW Norfolk, the 'Marly Drift' (now within the Sheringham Cliffs Formation), with the chalky Calcethorpe and Wragby tills of Lincolnshire and has regarded it as post-Anglian. He has invoked geomorphological evidence, including landscape incision and the disposition of deglacial landforms and deposits, to separate earlier (Anglian) and later (post-Anglian) glacial suites (e.g., Straw, 1965, 1973, 1983). The NGS went further in suggesting that glacial deposits from MIS 10 and MIS 6 could be recognized in North Norfolk, in the form of the Sheringham Cliffs Formation and the Briton's Lane Formation, respectively (Hamblin *et al*., 2005). However, OSL dating by Pawley *et al*. (2008), including the Briton's Lane type locality, obtained only Anglian (MIS 12) ages from these formations. Nonetheless, Westaway (2010) reconstructed an ice limit that he attributed to MIS 8 and envisaged, following Straw (e.g., 1973) and West (2009), that outwash from this ice drained via the valley now occupied by the Little Ouse and into the Waveney and, further north, by way of the Wensum valley to the Yare. He noted, however, an apparent biostratigraphical obstacle to verification of the latter outwash pathway in the form of Hoxnian (*sensu lato*) deposits in the Wensum Valley at Roosting Hill, Beetley (cf. West, 1991). These overlie glacigenic sediments that, in the view of Straw (1973), correlate with the well-known Salthouse Sandur deposits in the Glaven valley near the North Norfolk coast. The Salthouse Sandur is one of several glacigenic deposits in the Glaven valley that are inset below the level of the deposits at Briton's Lane, but which are undated. Lee *et al*. (2013) have argued that these lower-level sediments represent the latest stages of the waning Anglian glaciation, whereas Westaway *et al*. (2015) have pointed out that there is currently no basis to exclude a younger age.

A further constraint on the age and extent of post-Anglian–pre-Devensian glaciation in Norfolk, as noted above (cf. Westaway, 2010), arises from the application by Hoare *et al*. (2009) of the OSL technique to raised beach deposits at Morston, which has shown them to date from MIS 7 rather than the Ipswichian, as was previously supposed. Hoare *et al*. concluded that the Morston beach deposits had not been overtopped by glacial ice prior to MIS 2, when a thin representation of the Hunstanton Till was emplaced above them, with some degree of erosion, close to the southern limit of the Late Devensian glaciation.

Reconciliation of conflicting evidence in northern East Anglia requires further research (cf. Westaway et al., 2015). For example, the incision observed by Straw (1965, 1973, 1983) as preceding Devensian glaciation and allowing permanent establishment of the Wensum river system, would be ascribed by him to isostatic rebound during and after the MIS 8 glaciation. However, it is also possible that earlier isostatic rebound during Anglian deglaciation can account for this incision and for the geomorphological separation of the later suite of glacial evidence in the area, reconciling this evidence from the OSL dating (cf. Lee *et al*., 2013). Dating of the Salthouse Sandur and adjacent sediments, as well as proposed correlative deposits in adjacent catchments such as the Wensum and Bure (cf. Straw, 1973), is likely to be key to such resolution.

Regional comparison: the east coast further north

If the Tottenhill delta is correctly attributed to MIS 6 (see above) then a lobe of ice in that later glaciation reached into the Fen Basin without disruption of Trent drainage in the area around and upstream of Tattershall, since that drainage persisted until the latest Devensian (Bridgland *et al*., 2014, 2015). It also seems not to have impinged upon the east coast of England in the Humber region, since MIS 7 deposits have survived in the Foulness valley around South Cave, including (but perhaps not exclusively at) Bielsbeck Farm (Halkon, 1999, 2003; Schreve, 1999). These deposits, presumed to represent a pre-Devensian (Yorkshire) Derwent–Ouse system, survived the nearby encroachment of Late Devensian glaciation because of their location within Glacial Lake Humber rather than beneath the ice sheet; i.e. the MIS 2 Vale of York ice did not reach the Bielsbeck area (cf. Straw, 2002).

Moreover, recent work much further north, at Warren House Gill, Horden, County Durham, has suggested that the complex glacial sequence there comprises Late Devensian deposits overlying late Middle Pleistocene glacigenic sediments that are no younger than MIS 8, perhaps indicating that MIS 6 ice did not reach mainland England even this far north (Davies *et al*., 2012, 2013).

Regional comparison: the North Sea

Two phases of ‘Saalian’ glaciation have been envisaged in the North Sea basin (Ehlers, 1990). The earlier phase is represented by ‘early Saalian’ (MIS 8) tills, preserved offshore from the Netherlands. A requirement for a British ice sheet occupying part of the southern North Sea basin has been suggested in order to explain south-easterly ice flow onshore in the Netherlands (Rappol *et al*., 1989; Graham *et al*., 2011). Further evidence for this earlier advance was provided by Beets *et al*. (2005), who described borehole evidence in the southern North Sea for an extensive ice sheet during MIS 8, overlain by shallow marine sands correlated with MIS 7. This view was supported by Meijer and Cleveringa (2009) but Laban and van der Meer (2011) were circumspect about the interpretation.

Evidence for the 'later Saalian' (MIS 6) ice advance is provided by a glacial planation surface and overlying by glacigenic sediments, which can be traced across large parts of the North Sea (cf. Graham *et al*., 2011). Tunnel valleys of supposed Saalian age have been identified across the North Sea basin (e.g. Cameron *et al*., 1987; Wingfield, 1989; Huuse and Lykke-Andersen, 2000), although none have been directly dated. In the central North Sea, recent mapping has identified up to seven tunnel valley generations, consistent with phases of repeated subglacial incision during MIS 12, 10, 8 and 6 (Stewart and Lonergan, 2011).

Tills of demonstrable 'Saalian' age have been found mainly in the southern North Sea (e.g. Laban and van der Meer, 2004, 2011; Beets et al., 2005; Graham et al., 2011). A record of late Middle Pleistocene till in the central North Sea comes from BGS borehole 81/26 (58°29.5'N, 0°30.3'E), identified as a diamicton containing clasts of probable Scottish provenance within the Fisher Formation by Davies *et al*. (2011), who suggested that it might be the offshore equivalent of the Warren House Till (see above); however, it has also been suggested that this deposit is a local fill within a tunnel valley (Graham *et al*., 2011).

Discussion

Suggestions that there was lowland glaciation in England during MIS 8 (Straw, 2000, 2005; White *et al*., 2010) have been largely ignored. Several review publications have chosen to prioritize the potential for post-Anglian–pre-Devensian glaciation during MIS 10 and 6 (e.g. Lee et al., 2011, 2012; Busschers *et al*., 2007, 2008; Toucanne *et al*., 2009). The rationale for this might stem from the perception of MIS 8 as a less significant cold stage within the global oxygen isotope record of ice volume (cf. Kukla, 2005), albeit that the latter provides no evidence for the distribution or location of ice sheets. Nonetheless, as described above, MIS 8 glaciation has been envisaged for the North Sea Basin, where a subsiding sedimentary environment might be expected to have led to preservation of a more complete sequence. Substantial MIS 8 glaciation has also been proposed for Denmark (Houmark-Nielsen, 2011), Poland (Marks, 2011) and Ukraine (Matoshko *et al*., 2004; cf. Matoshko, 2011), although the widespread attribution of the earliest North European Saalian ice advances to MIS 8 (Šibrava *et al*., 1986) was rejected by Nývlt *et al*. (2011).

An important aspect of the British record is the widespread preservation in the East Midlands of deposits attributed to MIS 7, in some places directly overlying the Wragby Till (Fig. 5). An analogous situation is seen in East Anglia, where Hoxnian (MIS 11) interglacial deposits are commonly preserved overlying Anglian till (Fig. 5). If the tills in Lincolnshire were attributable to the Anglian (MIS 12) or to MIS 10, then it would be expected that overlying interglacial deposits would include examples attributable to MIS 11 and 9, or 9, respectively. That this is not the case, notwithstanding that it amounts to negative evidence, provides support for an MIS 8 age for the Wragby till and its correlatives. Molluscan evidence is critical to this argument, providing biostratigraphical and amino-stratigraphical age constraint for the sediments overlying the tills that are attributed here to MIS 8 (White *et al*., 2010; Penkman *et al*., 2011, 2012; Bridgland *et al*., 2014). Indeed, there is a kettle-hole fill overlying probable MIS 8 glacial deposits at Wing, Rutland (Fig. 5), although the pollen record from this sequence is indistinguishable from the Ipswichian (Hall, 1978, 1980) and calcareous fossils that might provide stronger biostratigraphical constraints are not preserved.

Distinguishing the products of different glaciations is a key issue in the resolution of continuing uncertainty about the number and timings of glaciations in the area discussed here and elsewhere. For many years a parsimonious approach has been taken, in which glacigenic sequences have been interpreted in terms of the minimum number of separate glaciations, effectively requiring clear evidence of interglacial conditions interbedded between glacial sediments. More nuanced indications, such as inter-relations with river terraces sequences and negative evidence related to interglacials preserved above glacial deposits, have rarely been considered. Both these lines of evidence have been used in the argument presented here for an MIS 8 age for the late Middle Pleistocene glaciation of the Middle and Lower Trent catchment. Thus, while it is believed that the products of both the Anglian (MIS 12) and Wragby (MIS 8) glaciations are widely distributed across the East Midlands, with both represented amongst tills of Oadby and Thrussington facies, the demonstration of unequivocal separation of the deposits of these glaciations, separated in time by two full Milankovitch 100 ka climate cycles, requires further research. One exception is the interpretation, as a result of TVPP investigation, of the highest terrace remnant in the Trent as outwash from the Anglian glaciation: the gravel capping Wilford Hill, in the southern outskirts of Nottingham (Bridgland *et al*., 2014; Table 1; cf. Clayton, 1953). There is an important contrast between the stratigraphical relations of this gravel, which was attributed by Bridgland *et al*. (2014) to the deglacially initiated Derwent–Soar ‘proto-Trent’ (Fig. 2), and the various glacially influenced deposits of the Hilton Terrace complex (Fig. 4), the latter being associated with the Wragby glaciation. The Wilford Hill Gravel is located a few km upstream of the Trent Trench ‘gorge’, cut through resistant Triassic bedrock. As Fig. 4 indicates, if the Wilford Hill outlier is projected downstream at the approximate gradient of the Trent terraces, its height above river level corresponds closely with that of the highest gorge sides, suggesting that the river has been incising this reach of its valley since the Anglian. It should be noted that an ice-marginal origin for the unusually straight Trent Trench was suggested by Lamplugh and Gibson (1910), Posnansky (1960) and Straw (1963); it is indeed possible to envisage such an origin, as part of the process of Anglian deglaciation, although (as noted above) the overall interpretation of the region requires that the gorge was reoccupied following glaciation of the Middle and Lower Trent region during MIS 8.

Conclusions

This review of the evidence for late Middle Pleistocene glaciation on the western flank of the southern North Sea, in the light of recent research in the wider Trent system during the TVPP, finds that the most compelling arguments point to extensive ice cover during MIS 8: its extent well within the footprint of Anglian ice but substantially greater than the Late Devensian ice sheets. Conversely, there is no compelling evidence for widespread lowland glaciation during MIS 6 on the western flank of the southern North Sea Basin north of the Wash. The best evidence for the attribution of glacigenic deposits in this region to MIS 8 comes from biostratigraphy, reinforced by amino-acid geochronology. However, there is reliance, for attribution to

MIS 8 rather than MIS 10, on arguments from uplift/incision modelling and the negative evidence of non-occurrence of sediments that can be assigned to MIS 11–9 inclusive. Given that Allan Straw reached similar conclusions previously from different lines of reasoning, attempts are made to reconcile his predominantly geomorphological evidence with that from the TVPP, with its basis in the river terrace stratigraphy from the Trent. Further research will be required to substantiate or modify aspects of this record; in particular, work is needed to distinguish between the glacial deposits of Anglian and post-Anglian age in the wider region beyond the range of the Late Devensian ice sheets, notably in the Middle Trent, in northern East Anglia and in the South Midlands.

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Tables:

Table 1 – Correlation of Quaternary sediments in the wider Trent catchment area, showing MIS attribution (after Bridgland *et al*., 2014). Note that the Thrussington and Oadby tills appear in both MIS 12 and MIS 8; it is indeed envisaged that these names have been applied to tills of both ages, such that they should perhaps be regarded as facies, representative of tills from western and eastern sources (respectively). Distinguishing genuine Anglian and 'Wragby' age tills, if both exist, will require detailed future investigation.

Figures:

Fig. 1 Section through the sequence in the Lower Trent (including the modern Lower Witham) valley, showing the relation between the terrace sequence and glacial deposits. The bifacetted nature of the Eagle Moor–Martin Terrace is depicted. MIS correlations are circled. After Bridgland *et al*. (2014).

Fig. 2 Palaeodrainage evolution of the Trent catchment (modified from Bridgland *et al*., 2014). A – Bytham River (pre-Anglian), B – Post-Anglian Derwent–Soar palaeo-Trent river system, C – Post-Wragby glaciation Trent system, D – The Devensian glaciation of the Lower Trent, showing the possible breaching of the former Trent–Ouse watershed by overflow from Lake Humber, E – Early post-glacial drainage system, with separation of the Trent and Witham.

Fig. 3 Location of MIS 7 deposits in and near the Lower Trent catchment. These generally occur within the Balderton–Southrey Formation of the Trent (or tributary equivalents, in the case of the Bain): Norton Bottoms Quarry (and nearby temporary exposures at Norton Disney and Brough); Whisby Quarry and nearby boreholes revealing the Thorpe on the Hill Bed (cf. Maddy, 1999); Southrey, from boreholes at Coronation Farm and nearby Stainfield; Tattershall Thorpe Quarry. In the sites downstream of Lincoln these deposits overlie Wragby Till. For further details, see Bridgland *et al*. (2014). The MIS 7 locality at Bielsbeck Farm, in the palaeo-Ouse system, is also shown.

Fig. 4 Long profiles of the Middle and Lower Trent terraces (after Bridgland *et al*., 2014). In the Middle Trent glacial deposits, assigned to MIS 8, fill the Elvaston Channel to the level of the Chellaston glacial deposits. The relation of the Wragby Till to the terraces downstream of Lincoln is shown in Fig. 1.

Fig. 5 Distribution of late Middle Pleistocene interglacial deposits in SE Britain relative to glacial limits of the MIS 12, 8 and 2 glaciations. MIS 12 and 2 limits after Clark et al. (2004), MIS 8 limit after White et al. (2010); note that Straw (1973, 2011), Westaway (2010) and Westaway *et al*. (2015) have argued for a more extensive ice sheet during that stage.

Fig. 6 Suggested extent of MIS 8 ice (modified after Bridgland *et al*., 2014, 2015). Eastern and western ice sheets are differentiated. A lobe of eastern ice penetrating the Middle Trent valley is invoked to explain the till of Oadby facies in the Elvaston and Swarkestone channels (Brandon and Cooper, 1997), as well as low-level chalky diamicton to the south of Leicester (cf. Rice, 1968). Also indicated are glacial meltwater channels, including the Southorpe Channel of Langford (2004), and the Tottenhill glacial outwash delta (perhaps resulting from a later glaciation, in MIS 6). The inset shows the location of a North Sea borehole within which MIS 8 glacial diamicton has been reported (Beets *et al*., 2005). Lobes of western ice impinging on the Derwent valley are reconstructed based on data from Dalton (1945, 1957) and Straw and Lewis (1962). Note that Straw (1965, 1973, 2011) Westaway (2010) and Westaway et al. (2015) have envisaged MIS 8 glacial limits further south and east than that depicted here.

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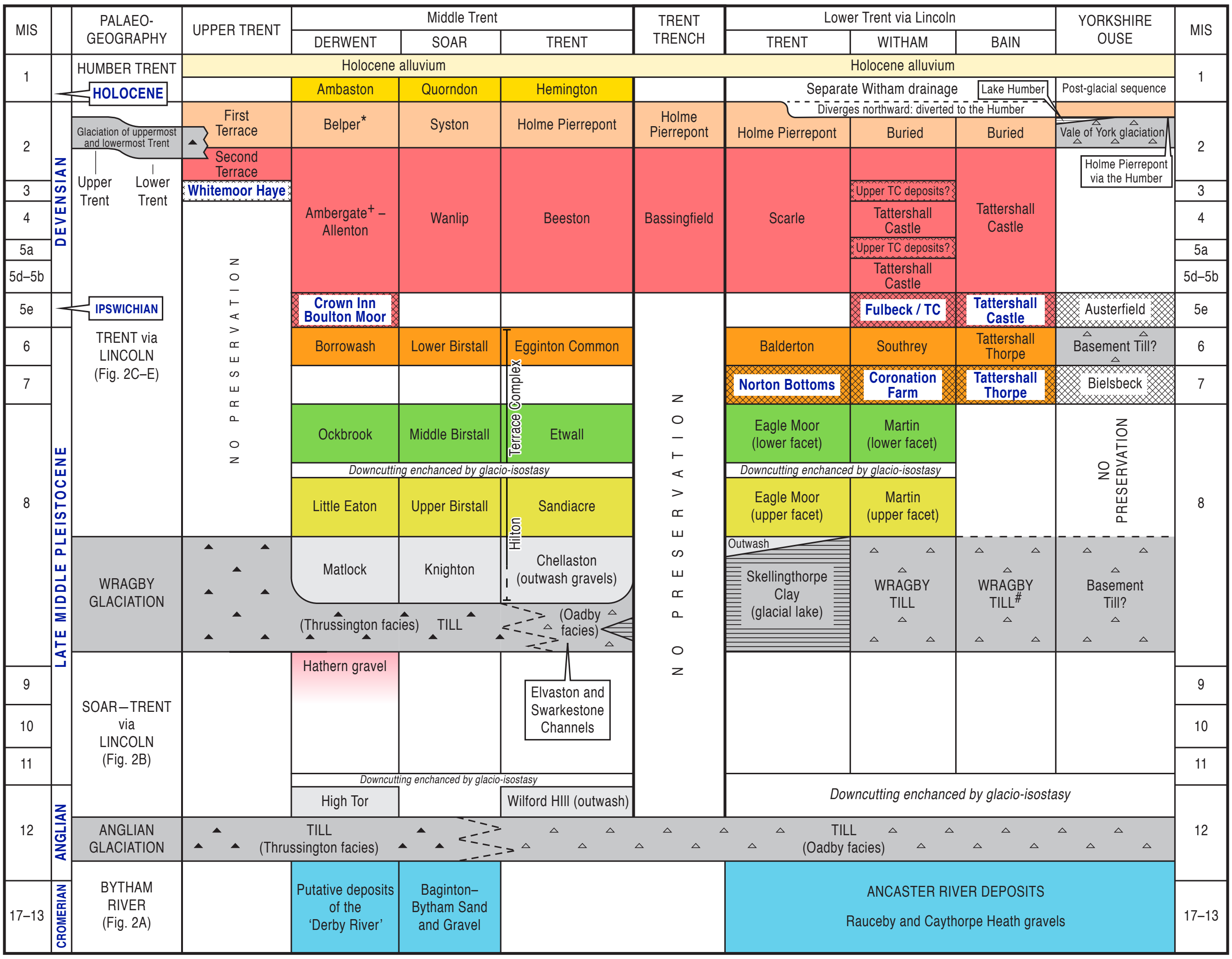
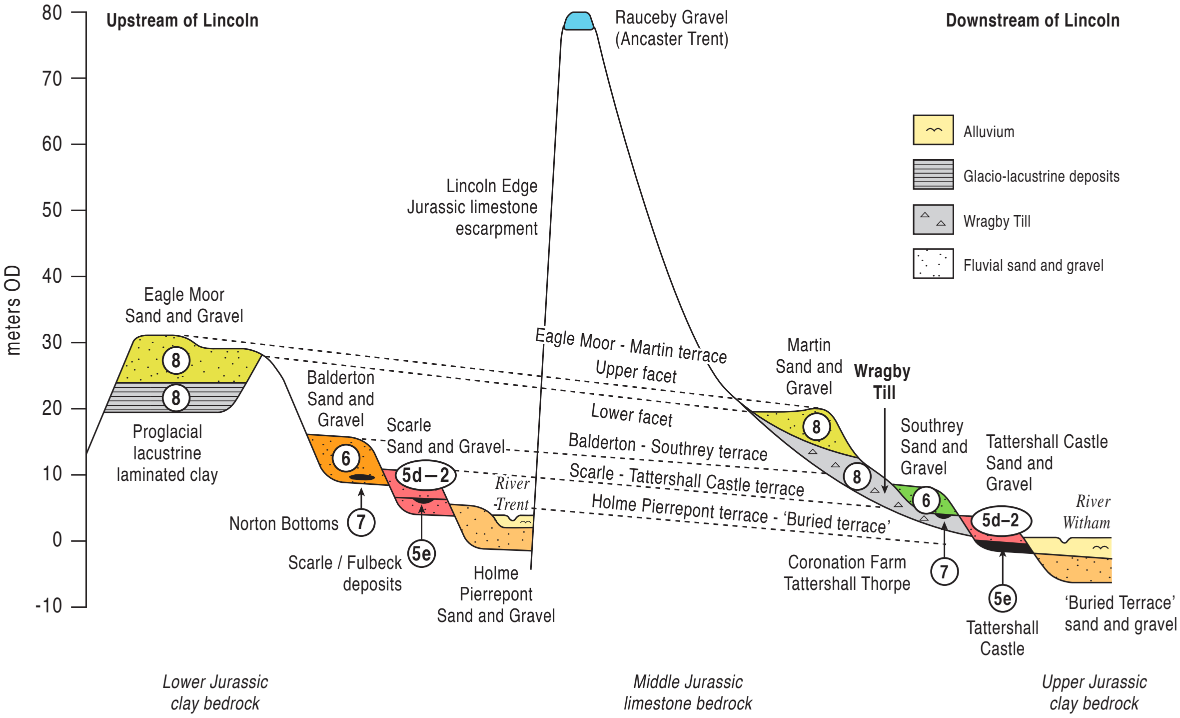


*Termed Chaddesen Sidings in the Lower Derwent by the BGS, although no outcrops are so named on DiGMap

+Waters and Johnson (1958) name retained for Middle and Upper Derwent system

#The Calcethorpe Till of Straw (1983() also occurs in the Bain Valley, upstream of the Tattershall area



Upstream of Lincoln
Downstream of Lincoln
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-10
Rauceby Gravel (Ancaster Trent)
Lincoln Edge Jurassic limestone escarpment
Alluvium
Glacio-lacustrine deposits
Wragby Till
Fluvial sand and gravel
Eagle Moor Sand and Gravel
Proglacial lacustrine laminated clay
Balderton Sand and Gravel
Scarle Sand and Gravel
Norton Bottoms
Scarle / Fulbeck deposits
Holme Pierrepont Sand and Gravel
River Trent
Eagle Moor - Martin terrace
Upper facet
Lower facet
Balderton - Southrey terrace
Scarle - Tattershall Castle terrace
Holme Pierrepont terrace - 'Buried terrace'
Martin Sand and Gravel
Wragby Till
Southrey Sand and Gravel
Tattershall Castle Sand and Gravel
River Witham
Coronation Farm Tattershall Thorpe
Tattershall Castle
'Buried Terrace' sand and gravel
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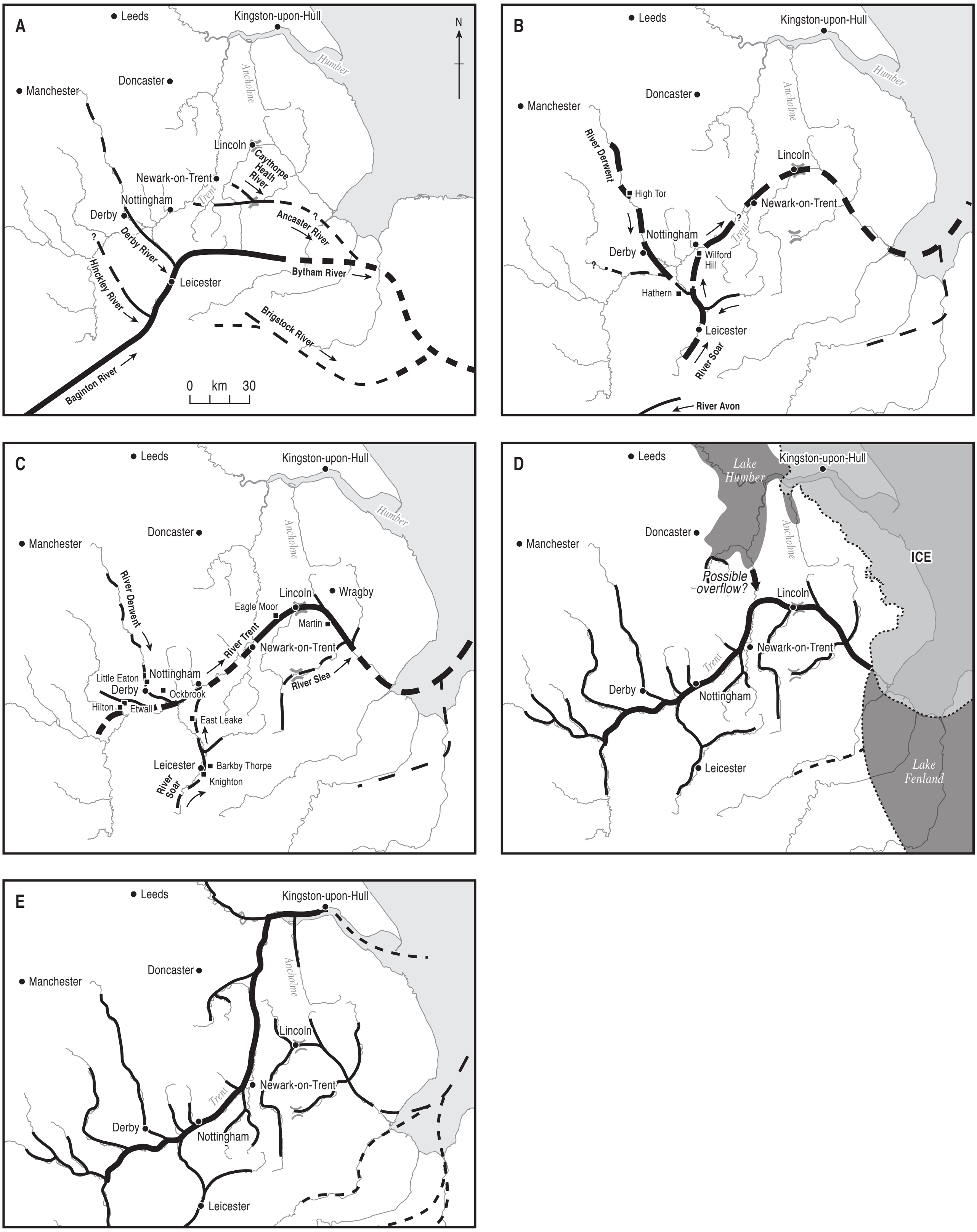
Lower Jurassic clay bedrock
Middle Jurassic limestone bedrock
Upper Jurassic clay bedrock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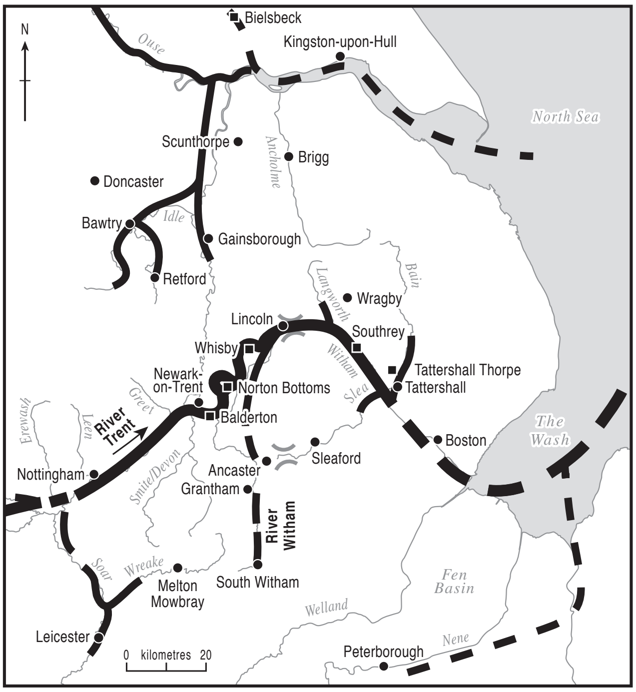
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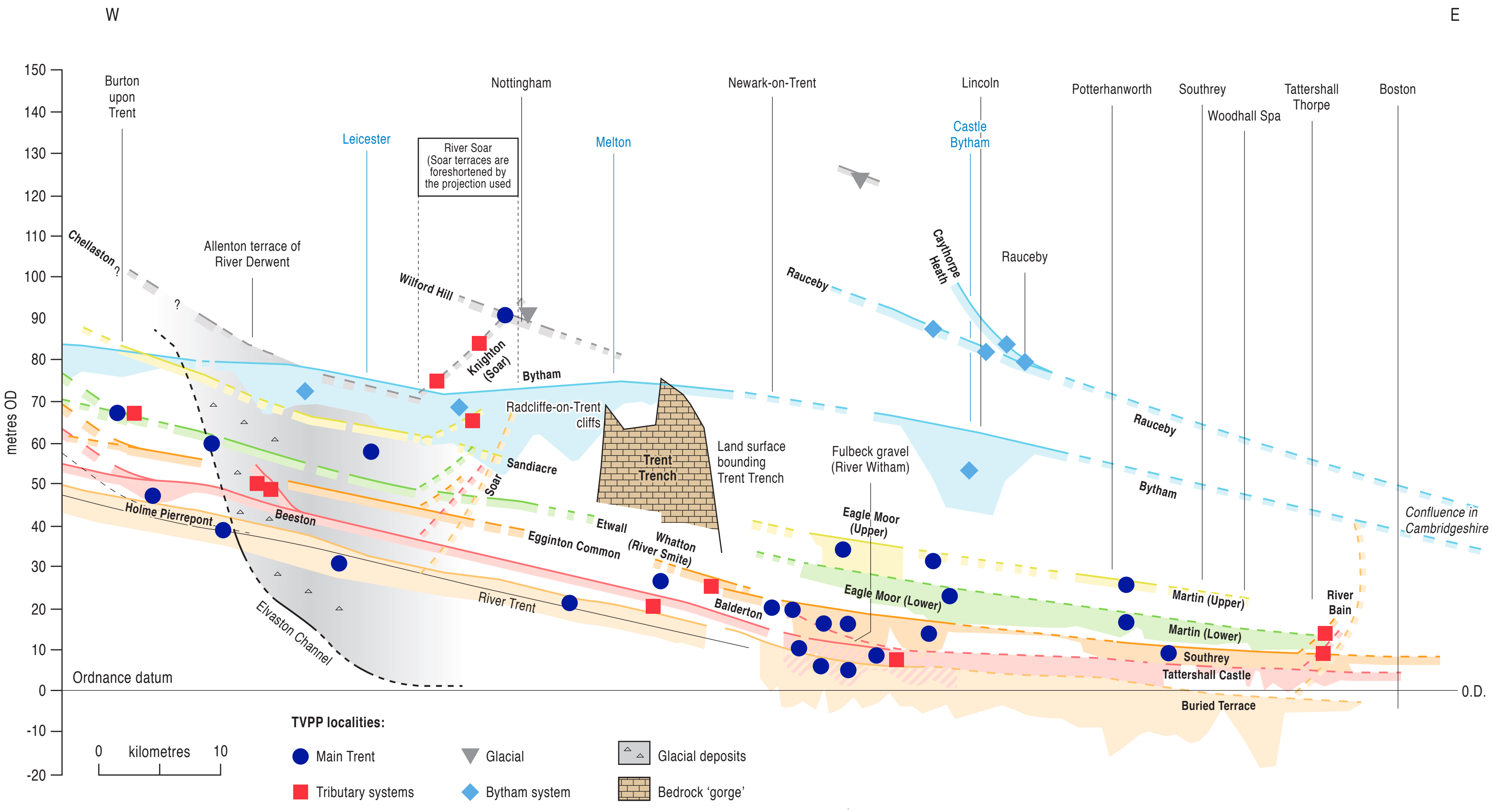
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Castle Bytham
River Soar (Soar terraces are foreshortened by the projection used
Chellaston
Allenton terrace of River Derwent
Wilford Hill
Knighton (Soar)
Bytham
Rauceby
Caythorpe Heath
Radcliffe-on-Trent cliffs
Trent Trench
Land surface bounding Trent Trench
Fulbeck gravel (River Witham)
Sandiacre
Soar
Etwall
Whatton (River Smite)
Egginton Common
Beeston
Holme Pierrepont
Balderton
Eagle Moor (Upper)
Eagle Moor (Lower)
Martin (Upper)
Martin (Lower)
Southrey
Tattershall Castle
Buried Terrace
River Bain
Confluence in Cambridgeshire
River Trent
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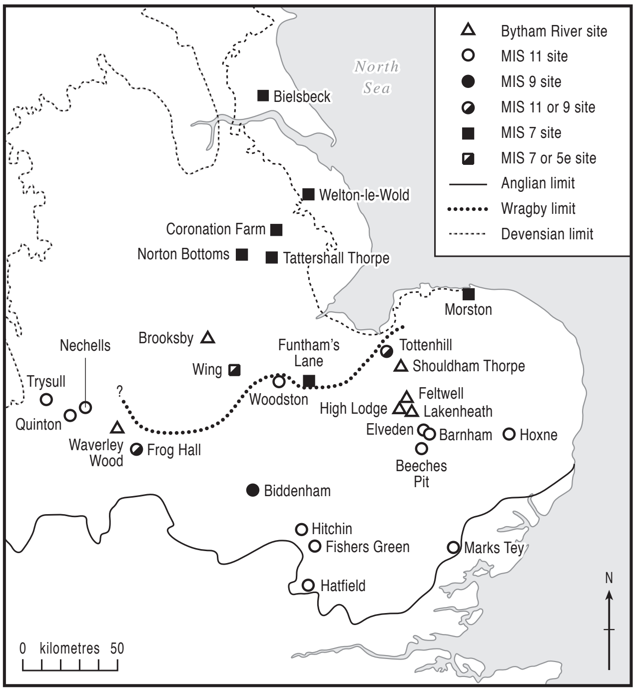
TVPP localities:
Main Trent
Tributary systems
Glacial
Bytham system
Glacial deposits
Bedrock 'gorge'


Bytham River site
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MIS 7 site
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Anglian limit
Wragby limit
Devensian limit
North Sea
Bielsbeck
Welton-le-Wold
Coronation Farm
Norton Bottoms
Tattershall Thorpe
Morston
Brooksby
Nechells
Tottenhill
Funtham's Lane
Shouldham Thorpe
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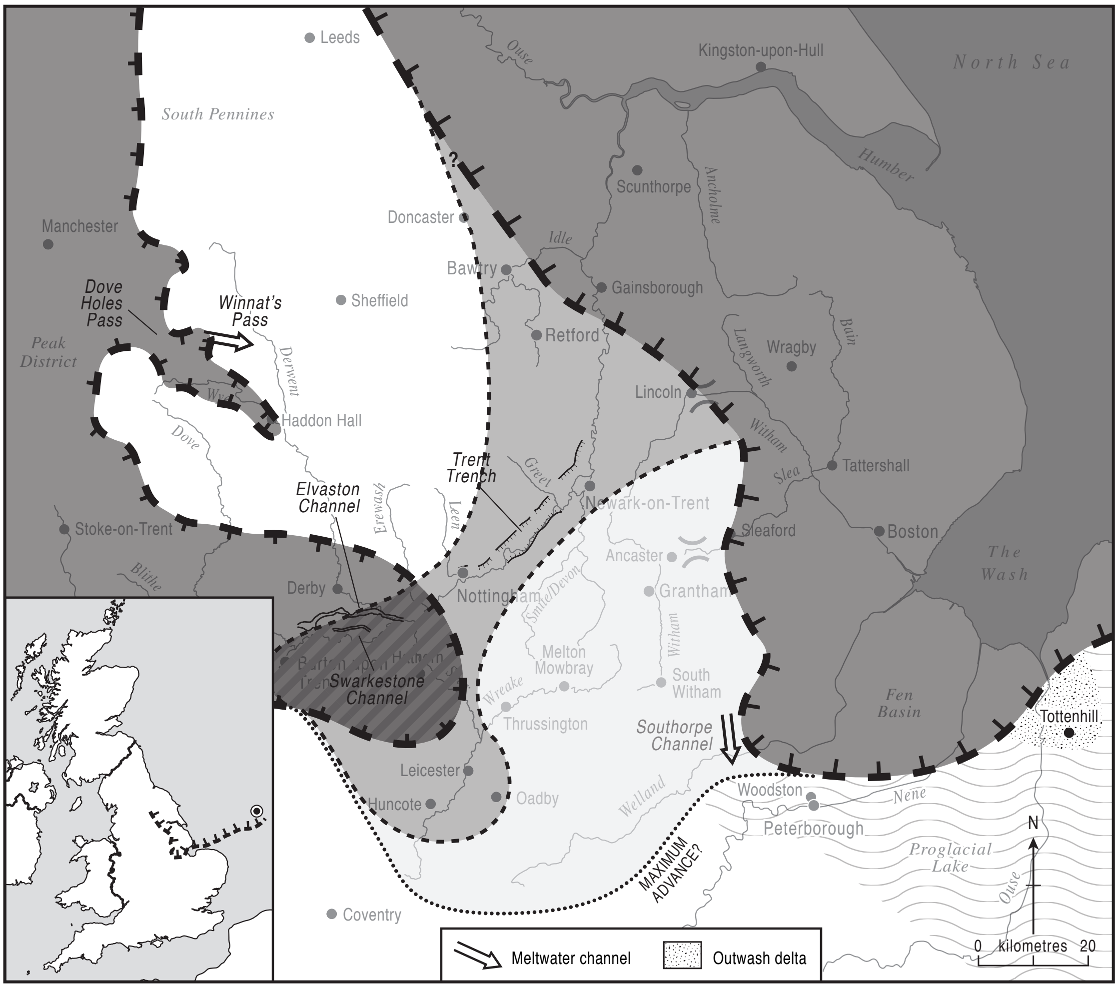
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Derby
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Grantham
Smite/Devon
Witham
Swarkestone Channel
Melton Mowbray
South Witham
Fen Basin
Wreake
Thrussington
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